Quantum Electronic Solids

07 March 2013

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Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 MAR 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Quantum Electronic Solids**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Office of Scientific Research ,AFOSR/RTD,875 N. Randolph,Arlington,VA,22203**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**21**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

NAME: **Quantum Electronic Solids**

BRIEF DESCRIPTION OF PORTFOLIO:

Physics and electronics at the nanoscale: superconductivity, metamaterials and nanoelectronics - exploiting quantum phenomena to create faster, smarter, smaller and more energy-efficient devices

SUB-AREAS IN PORTFOLIO:

Superconductivity: find more-useful materials for high magnetic fields, microwave electronics, power reduction and distribution

Metamaterials: microwave, IR & optical sensing and signal processing with smaller sizes and unique properties

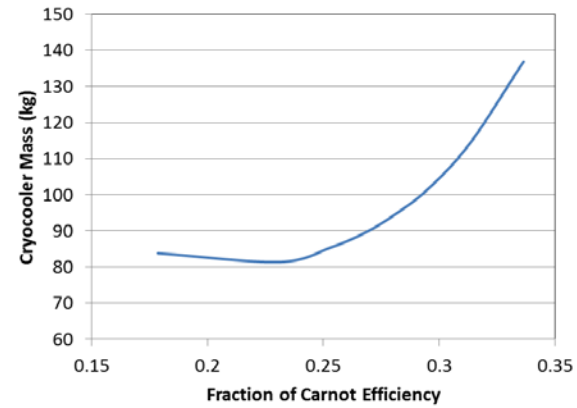
Nanoelectronics: NTs, graphene, diamond, SiC for sensing, logic & memory storage

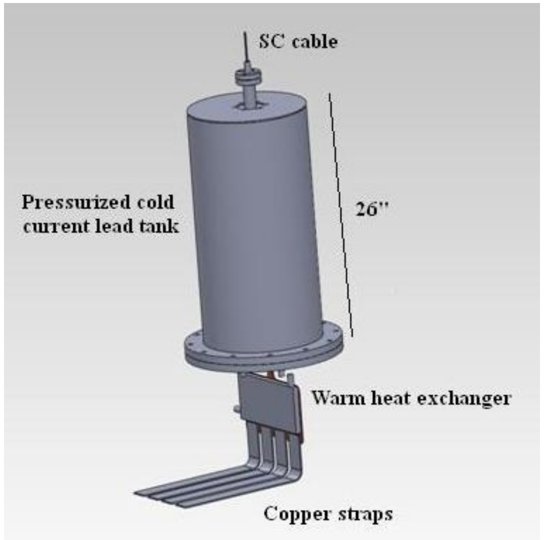
SC Power Transmission for DE

A. Dietz, Creare Inc., L. Bromberg, MIT

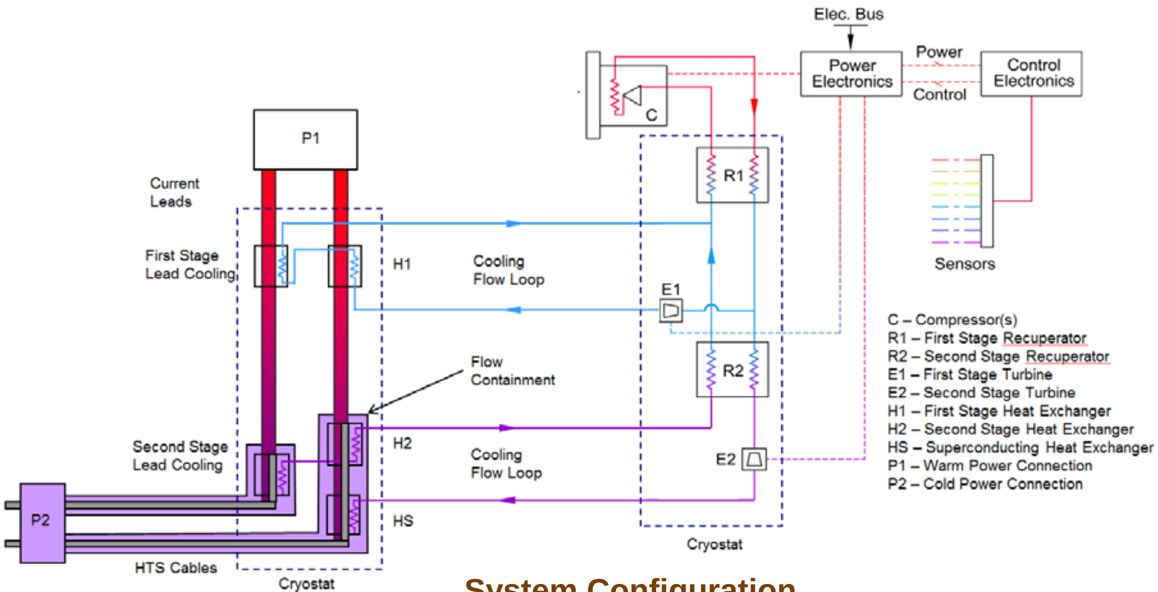
- Two-stage current leads with integrated heat exchangers cooled by cycle gas from a two-stage turbo-Brayton cryocooler
- Current lead design minimizes cold heat load and ensures even current distribution
- Cryocooler design offers high efficiency with low weight
- Advantages over copper cables
  - 90% less weight
  - 40% less power consumed

Cryocooler Performance





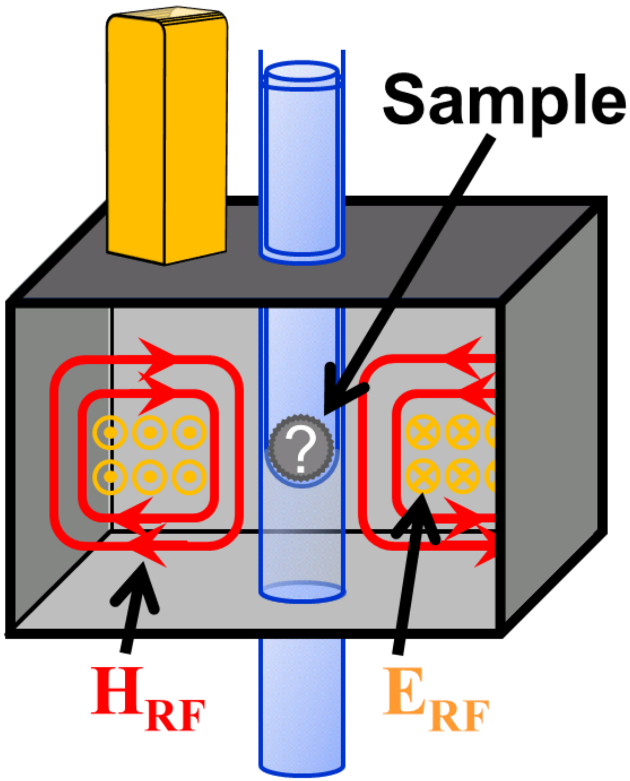
Current Lead Design

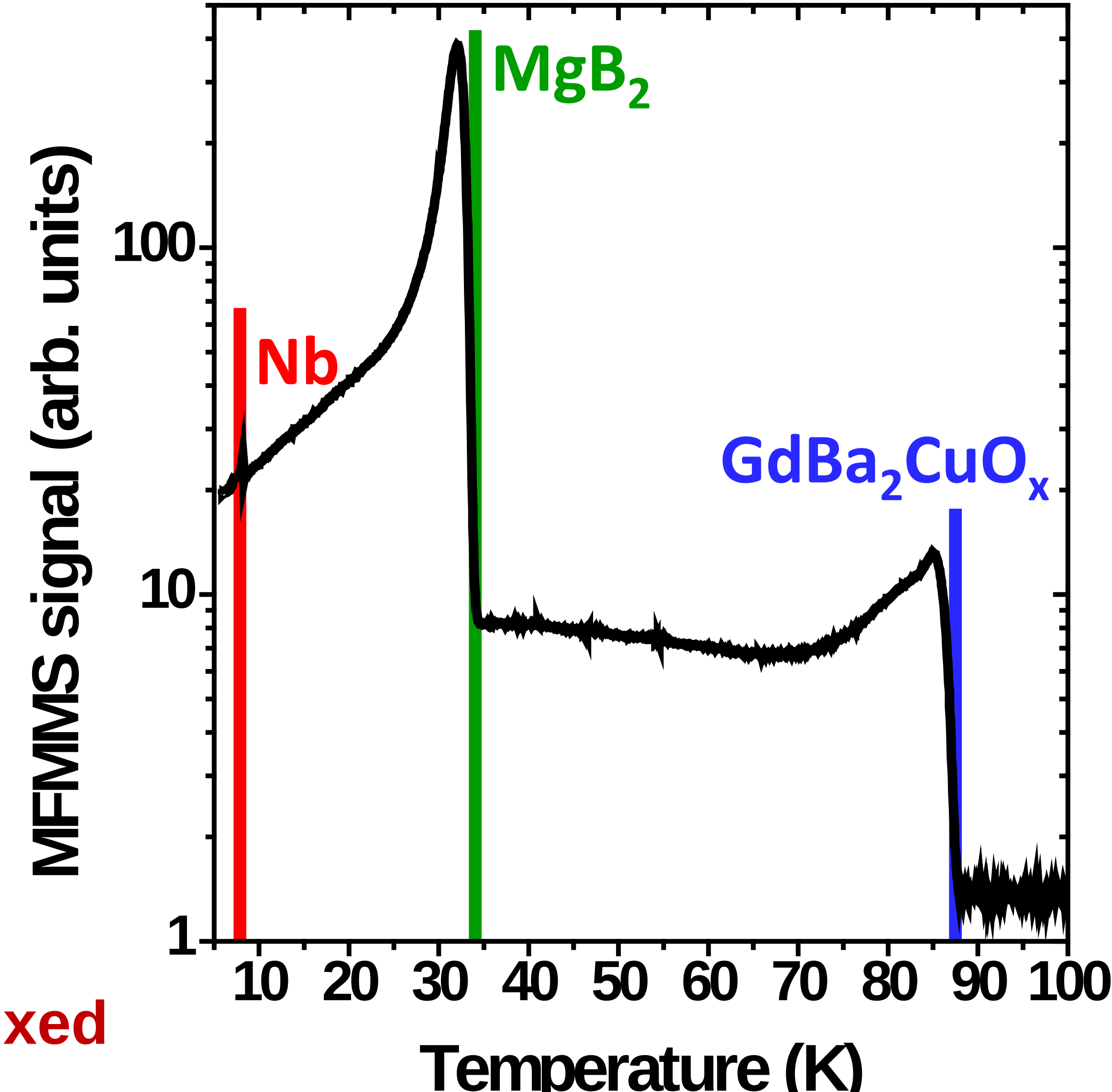


System Configuration

MURI Supersearch
Fast, Selective, Sensitive Scanning Method

Ivan K. Schuller, UCSD

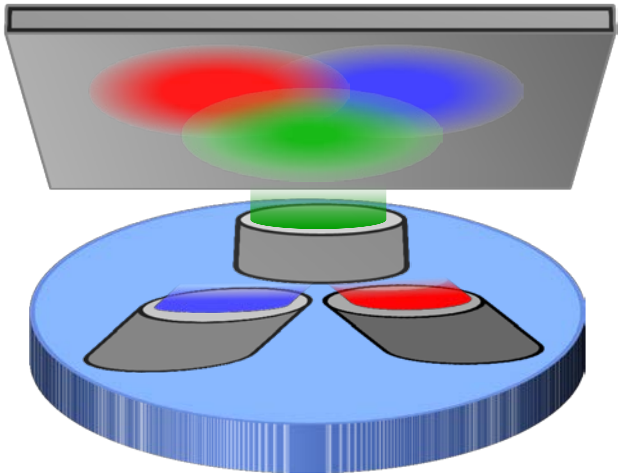




Study of intimately mixed superconductors

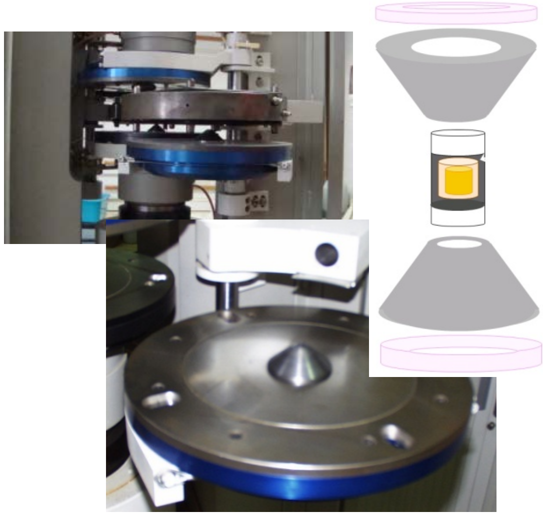
MURI Supersearch
New Superconductors Discovered

Ivan K. Schuller, UCSD



Phase Spread Alloys

Bulk Synthesis



- High-Pressure
- High-Temperature

✓ Service to Others

MFMMS

<u>Discoveries (#):</u>

Borides (10), Carbides (6), Calchogenides (4), Silicides (2), Bismuthates(1), Antimonides (1), Other Intermetallics (2)

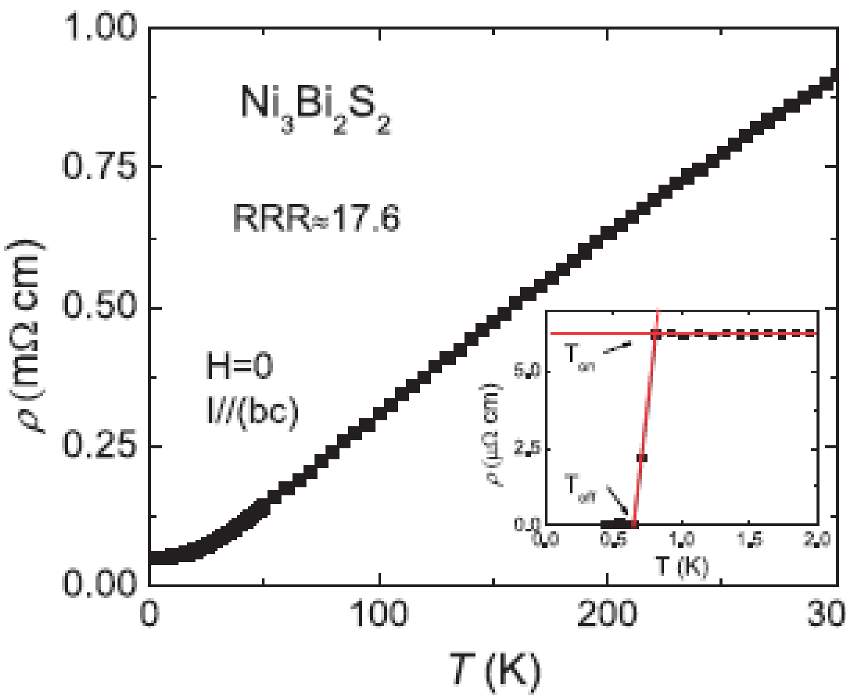
Meteorites

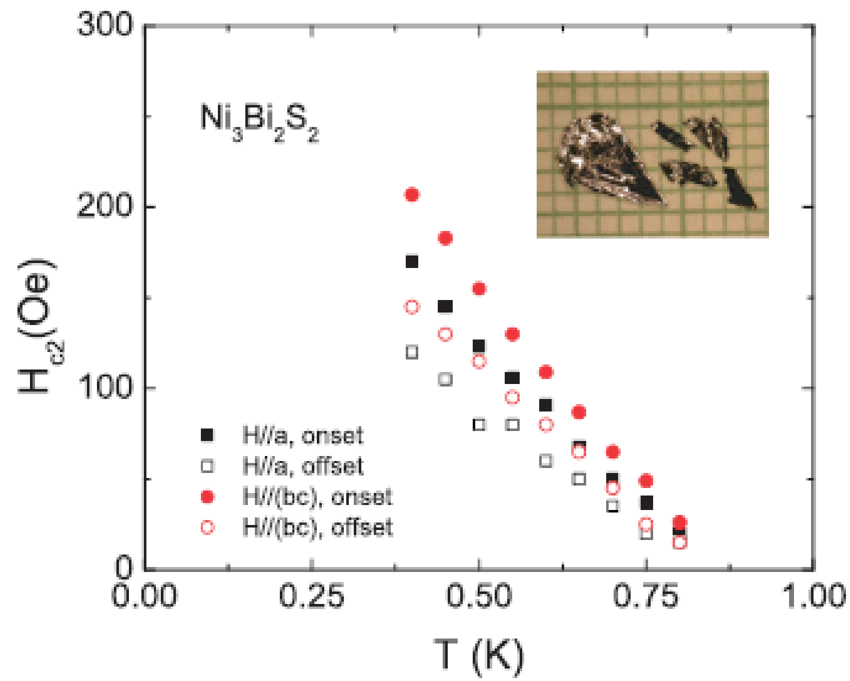
Empirical Search for New Superconductors

U Maryland-Iowa State-UC San Diego MURI (PI-R.L. Greene)

Development of viable solutions for the synthesis of sulfur-bearing single crystals

Xiao Lin, Sergey L. Bud'ko and Paul C. Canfield*



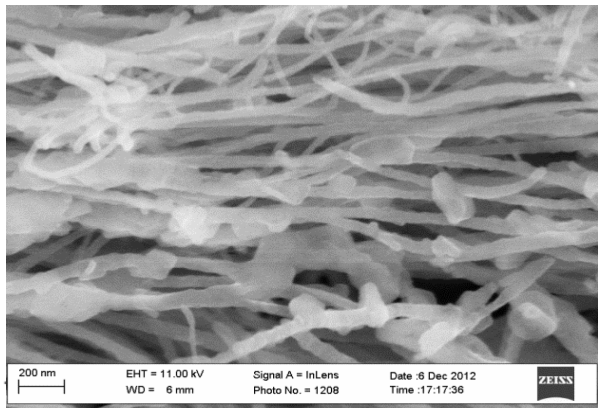


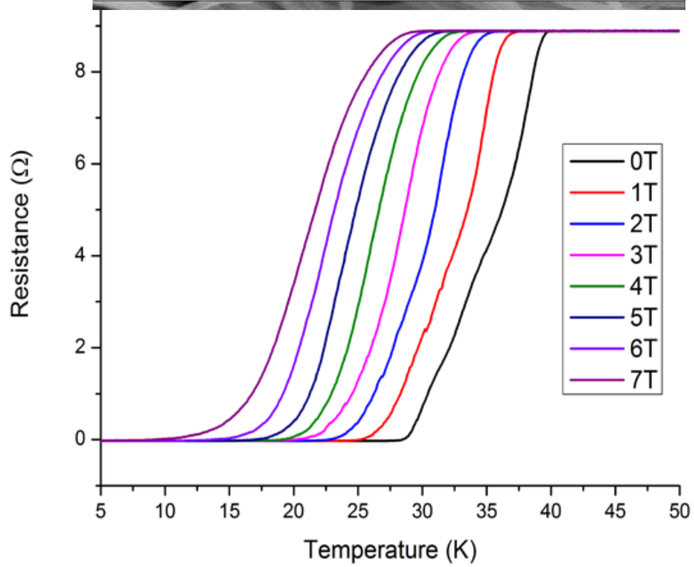
Have grown single crystals of mineral types: Parkerite (above, SC below 1K), Shandite, Paracostibite, and sulfide variants of olivine (not shown and not SC).

Superconducting Flexible Wire: $MgB2@CNT$; $FeSe@CNT$

A. Zakhidov, University of Texas at Dallas

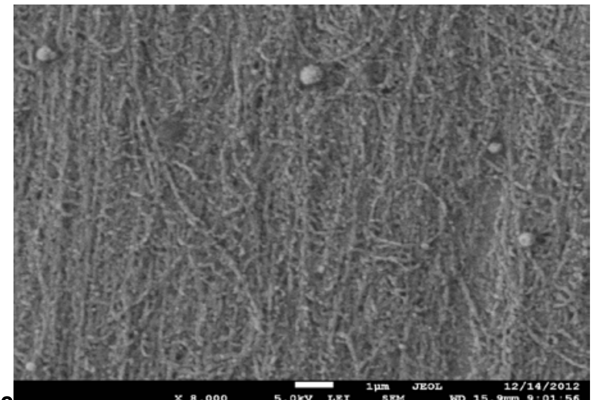
MgB_2 nanowires

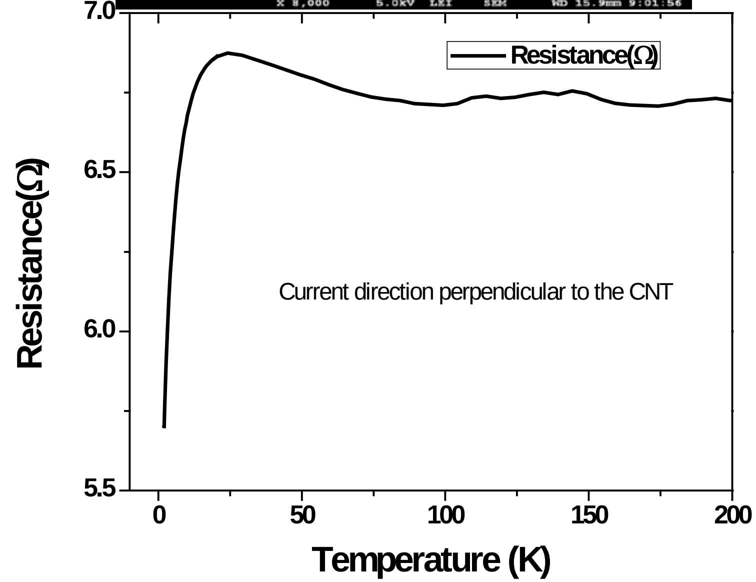




Resistance drops to exact zero after RF oxygen plasma treatment,

$FeSe_{0.5}Te_{0.5}$ on CNT

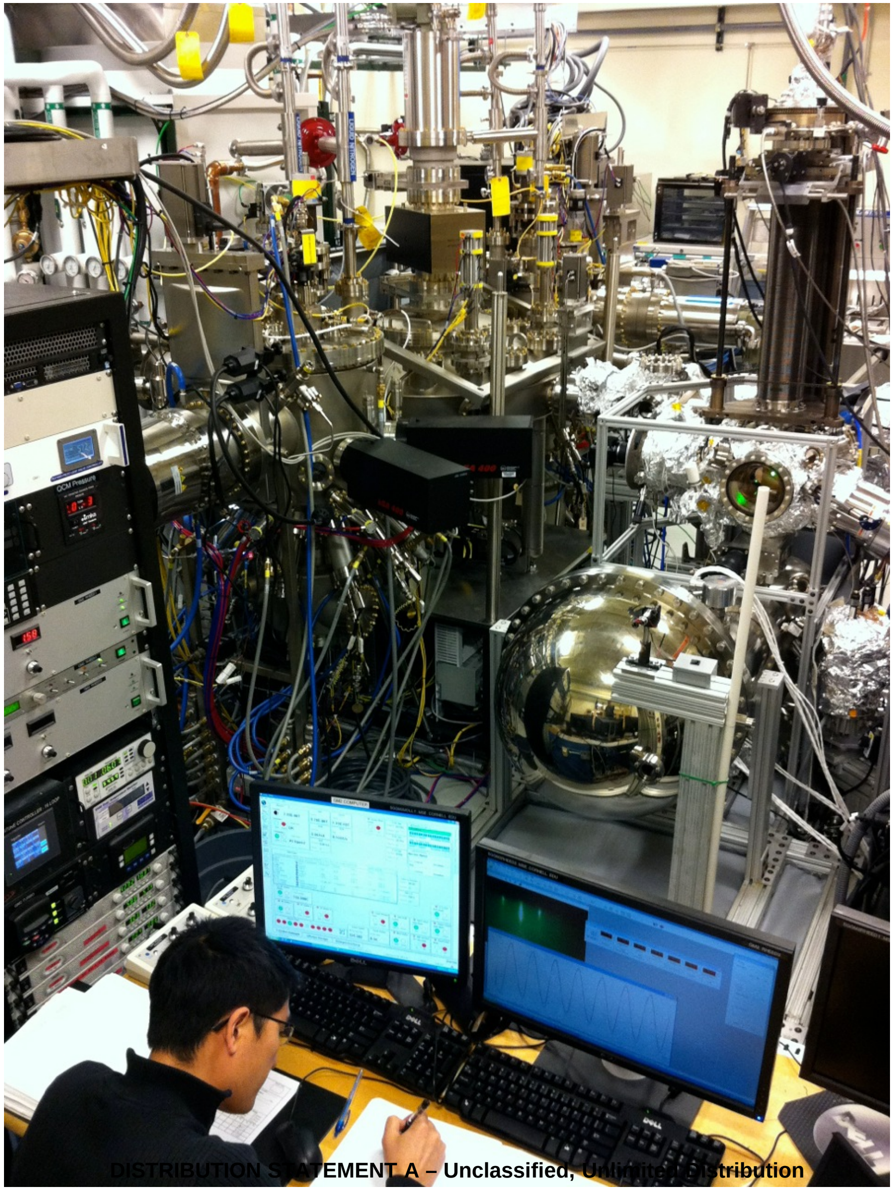




Resistance drops at Tc but not to zero : needs optimization of barrier coating.

Integrated MBE – ARPES

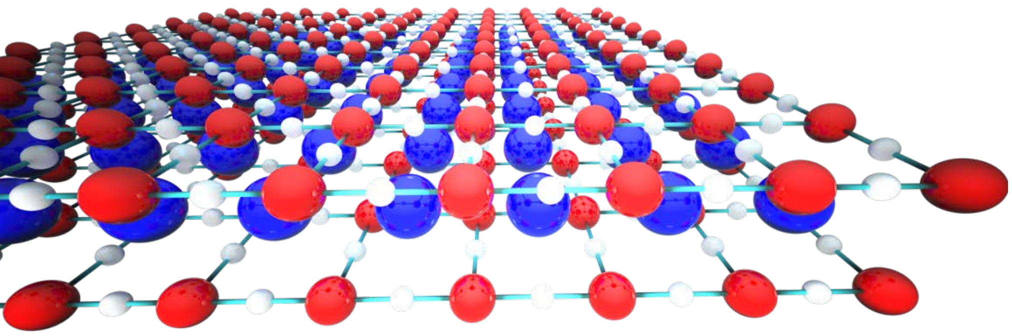
Kyle Shen, Cornell U.



Investigating the "Mother" of all High-T_c Superconductors

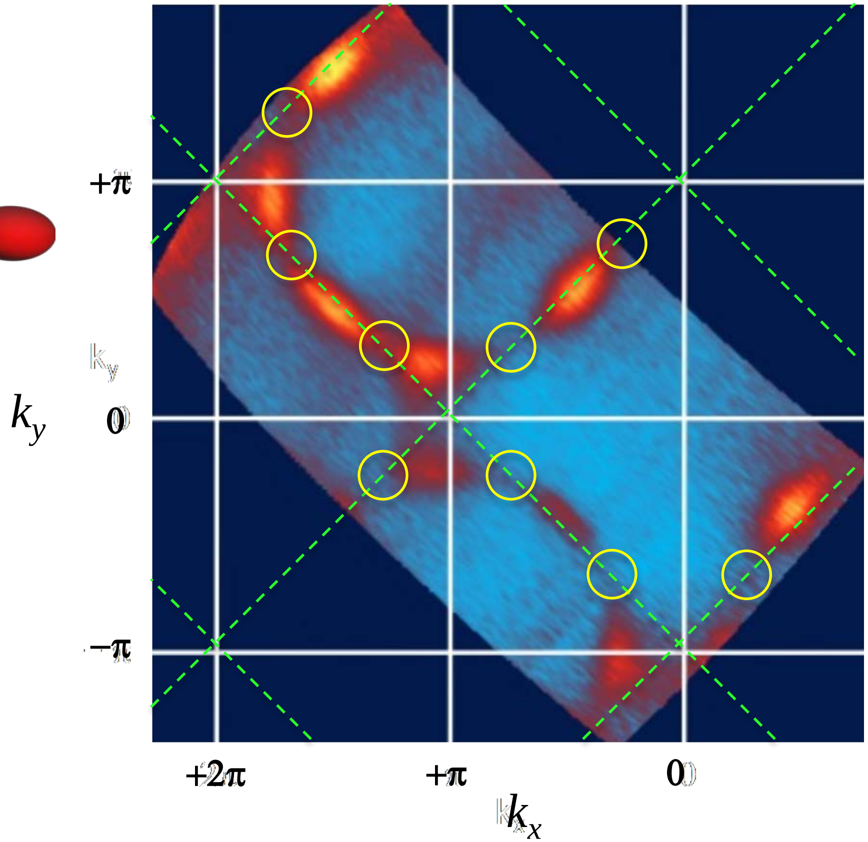
Kyle M. Shen, Cornell University

$Sr_{1-x}La_xCuO_2$ epitaxial thin films



- Simple, archetypal structure of cuprates (square, flat CuO_2 sheets)
- Can be doped either with holes or electrons (only ambipolar SC cuprate)
- Bulk single crystals do not exist (epitaxial stabilization)

ARPES measurements



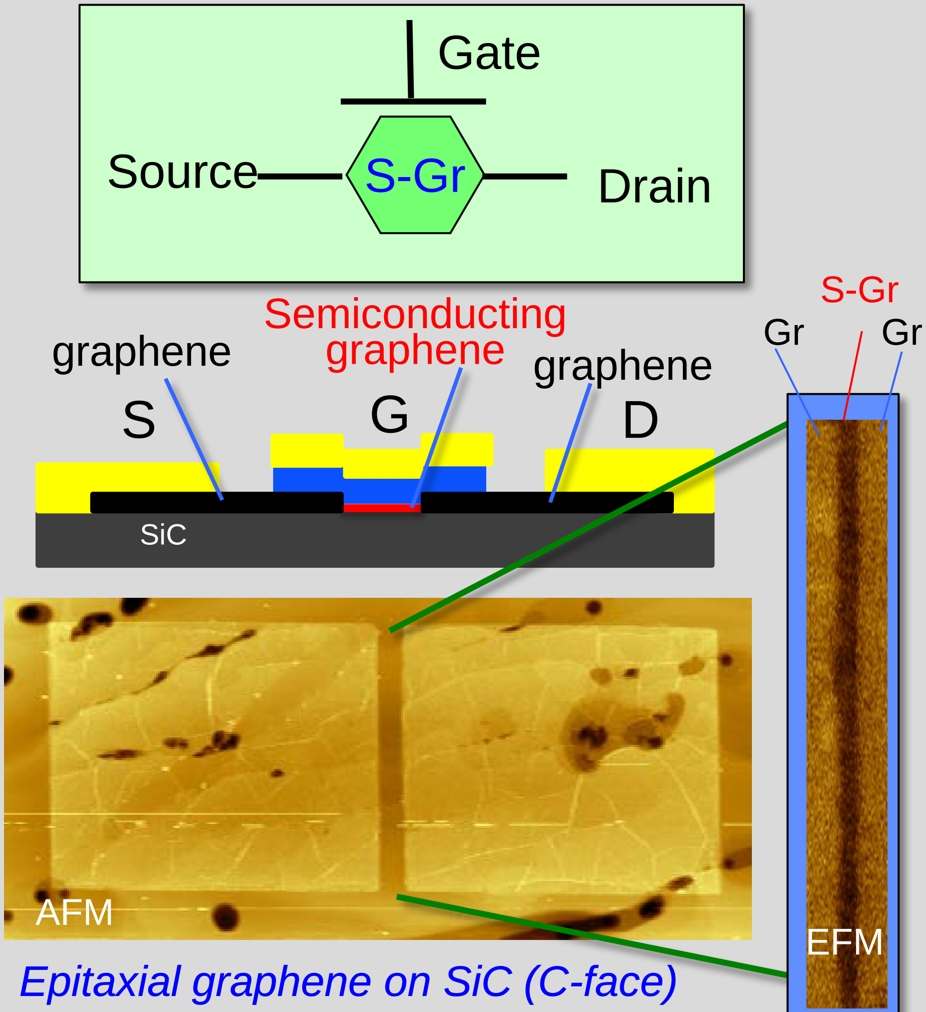
Regions of suppressed intensity on the Fermi surface (yellow circles) indicate presence of strong antiferromagnetic fluctuations

J.W. Harter *et al.*, *Phys. Rev. Lett.* (in press)

Semiconducting Graphene (S-Gr)

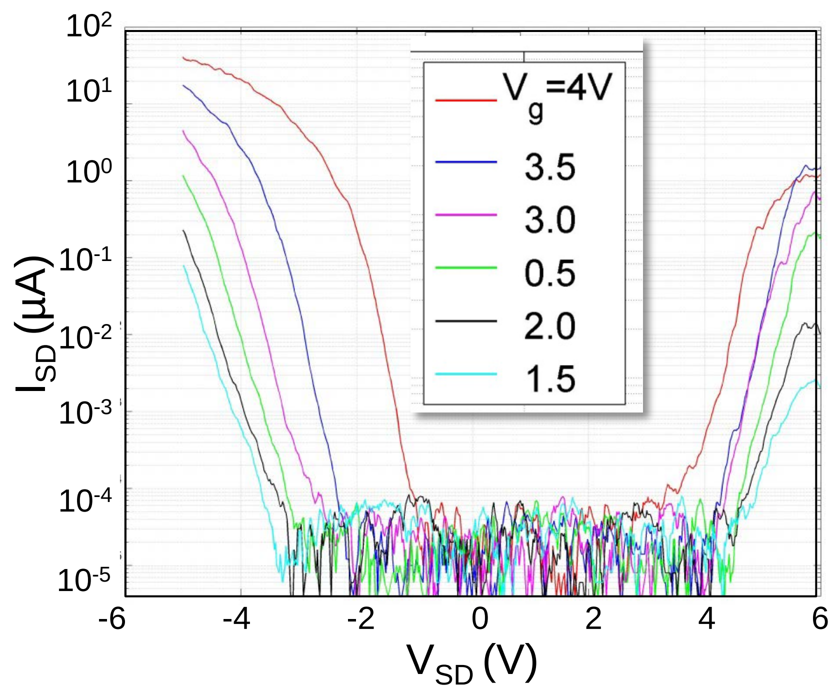
Walt de Heer, Georgia Tech

- SGr (bandgap~1eV) is graphene that is bonded to the SiC surface.
- It *seamlessly* connects to graphene to make atomically thin, gateable SGr-Gr junctions.
- Digital electronics is feasible; • SGr is stable at extreme temperatures;



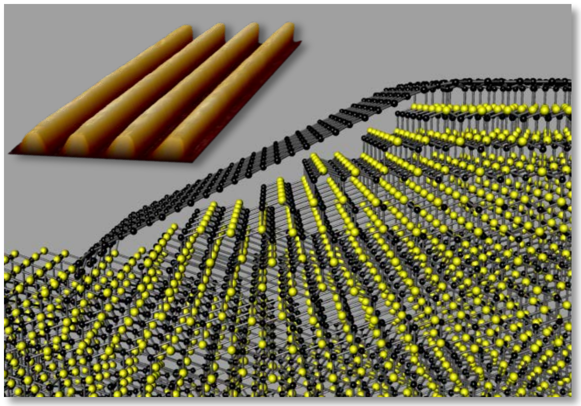
Epitaxial graphene on SiC (C-face)

On-off ratio > 10^5
Factor 10^4 greater than for pure graphene FETs.

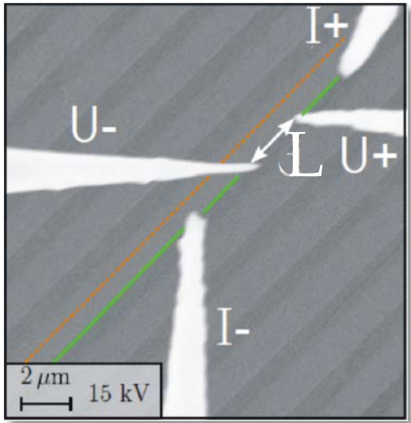


Room Temp Ballistic Transport in Graphene Nano-ribbons

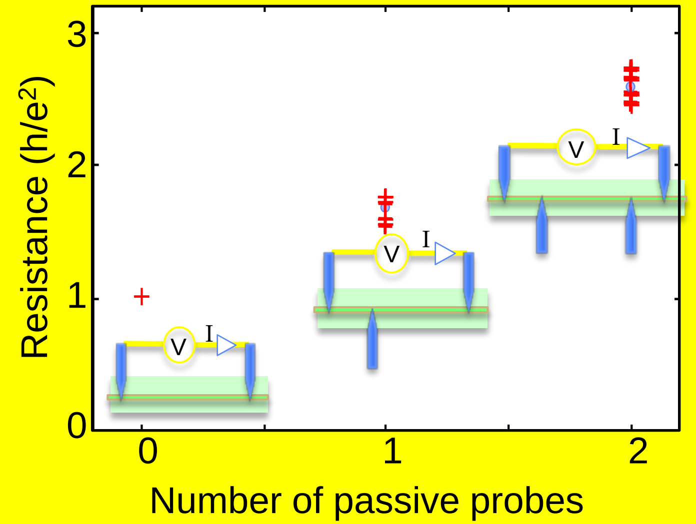
Walt de Heer, Georgia Tech

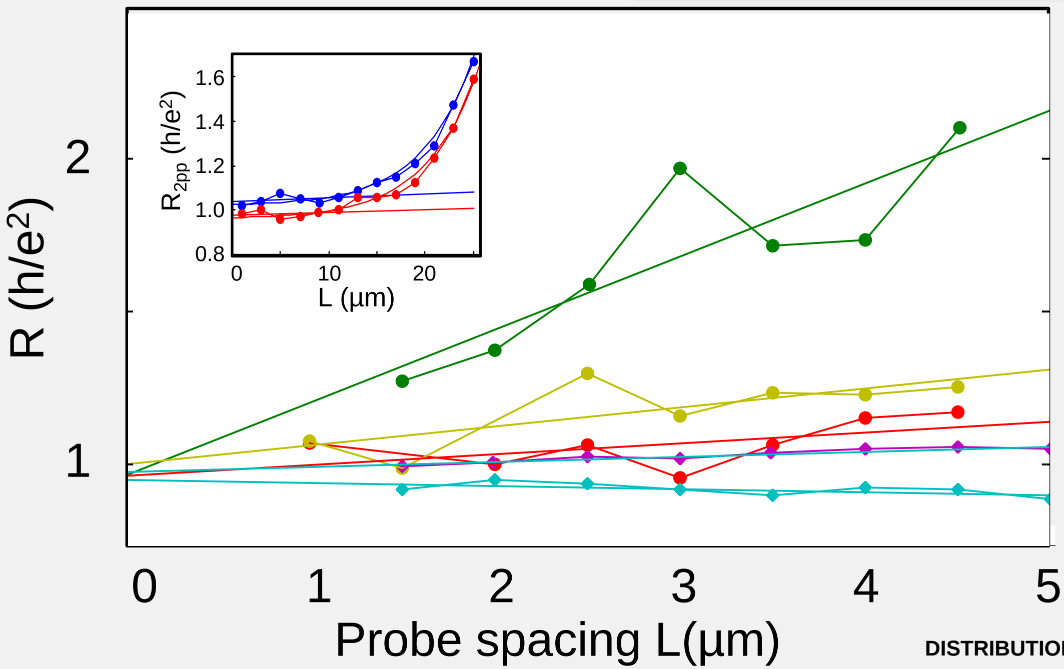


Graphene on crystallized sidewall



SEM image of four nano probes contacting graphene ribbon

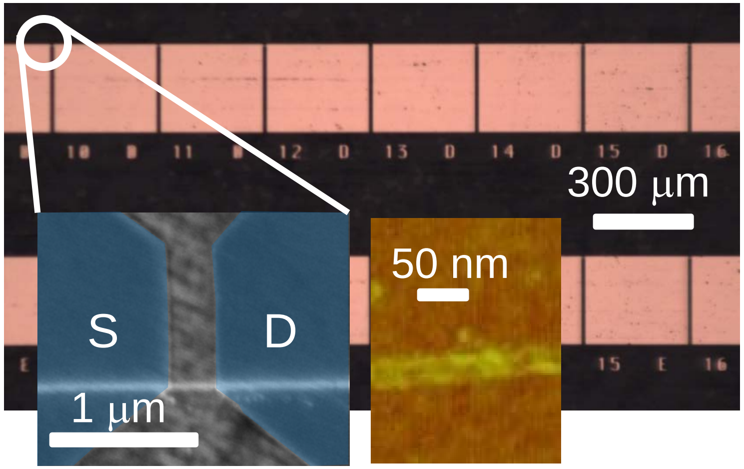




- 40 nm wide graphene ribbons grown on crystallized sidewalls of trenches etched in SiC are ballistic conductors.
- Resistances ($\approx h/e^2$=25.8 kΩ) are essentially independent of length and temperature.
- Touching a ribbon with a probe, scatters electrons and (reversibly) doubles the resistance. Touching it with 2 probes, triples it.

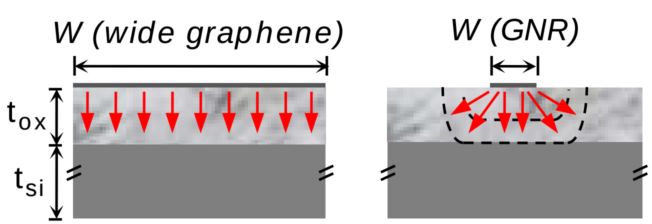
Nanoscale Interconnects from CVD Graphene

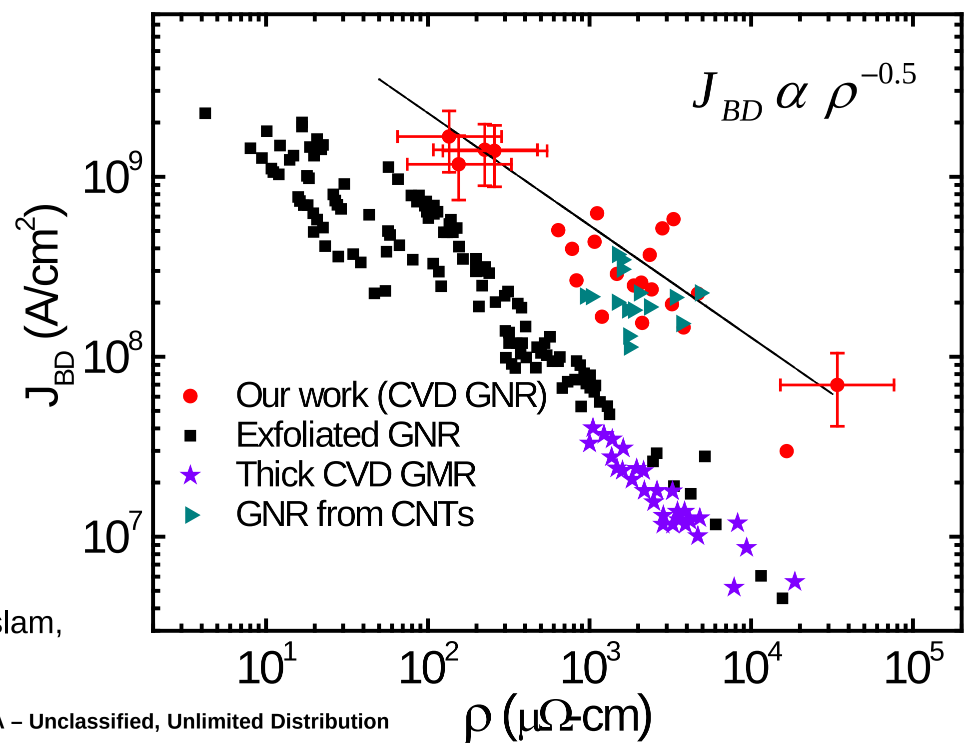
Eric Pop, UIUC



- Achieved record current densities >10^9 A/cm^2 in small GNRs due to improved heat dissipation through the substrate and contacts (see bottom left).
- Thermal engineering of the substrate and its interface with graphene can further improve the performance of GNRs

- First study of large-scale graphene nanoribbon (GNR) interconnects from graphene grown by chemical vapor deposition (CVD)
- Examined temperature range 2-900 K



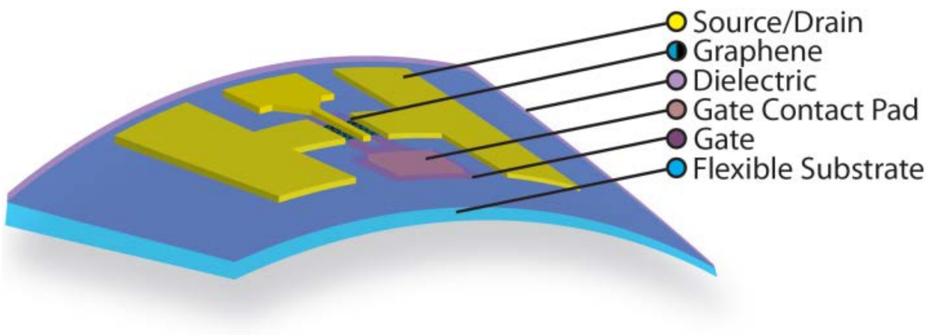


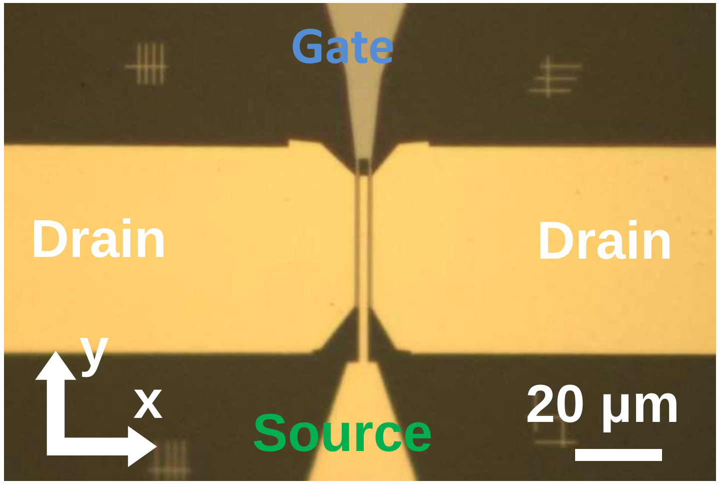
See: A. Behnam, A. S. Lyons, M-H. Bae, E. K. Chow, S. Islam, C. H. Neumann, E. Pop, *Nano. Lett.* 12, 4424 (2012).

Graphene Yields High Performance Flexible FETs

Ken Shepard and Jim Hone, *Columbia University*

Inherent flexibility of monolayer graphene, and its environmental inertness, make it a natural candidate for flexible electronics. GHz frequency response can be obtained with little sensitivity to strain, a major advance in flex-FET speed.





Questions: Stress, Performance, Fabrication

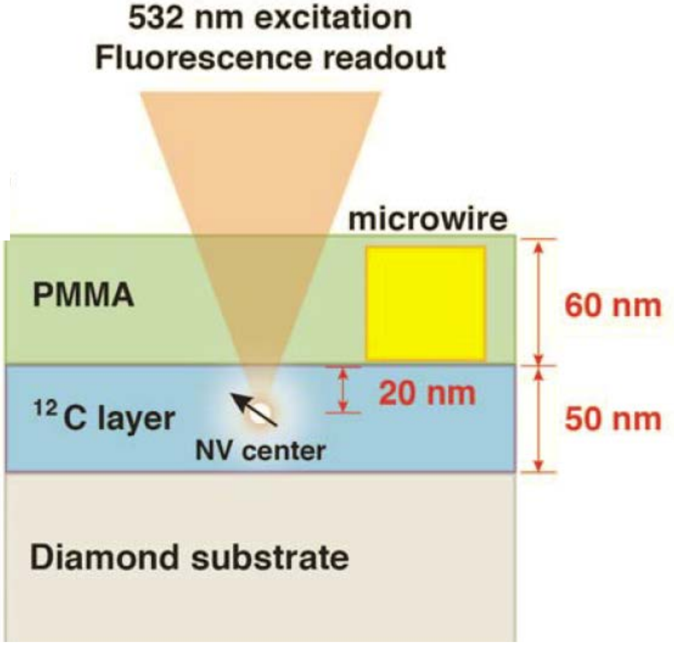
- **Back gate (gold-palladium alloy), PEN substrate**
- **Hafnium-oxide gate dielectric**
- **CVD graphene transferred over gates**

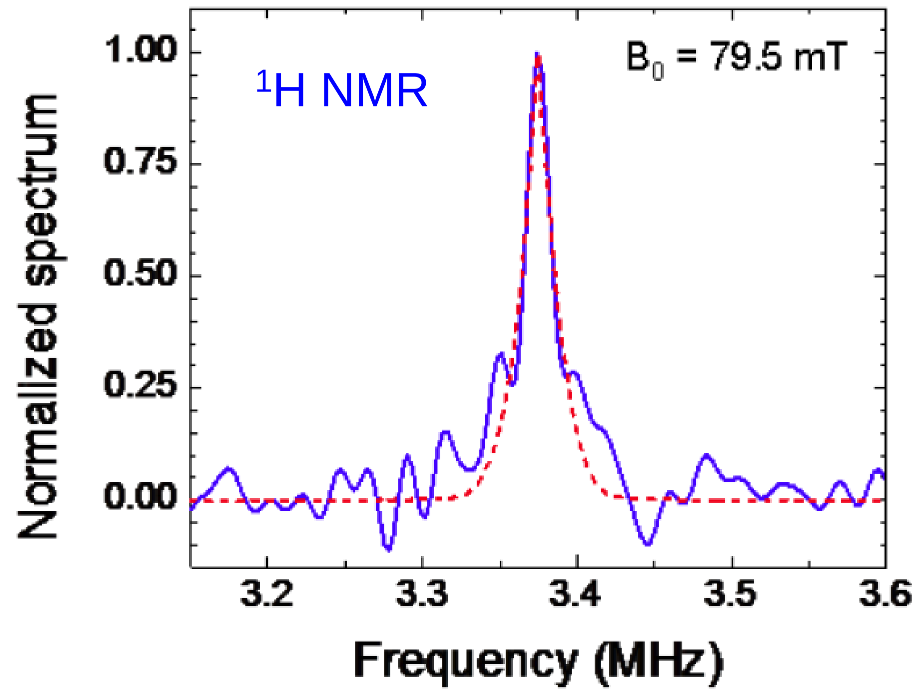
Performance

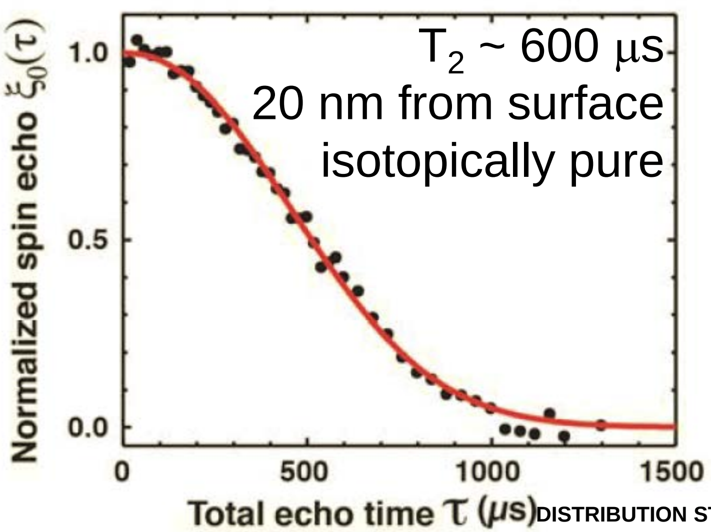
- **f_T, f_{max} of 10.7 GHz, 3.7 GHz w/o de-embedding**
- **f_T/f_{max}=0.35, entire strain range.**
- **Mobility, output resistance unchanged by strain; g_m ~1/2 its 0% strain value at ~2% strain**

Nanoscale NMR with a Single Electron Spin Sensor

D. D. Awschalom, *University of California – Santa Barbara*







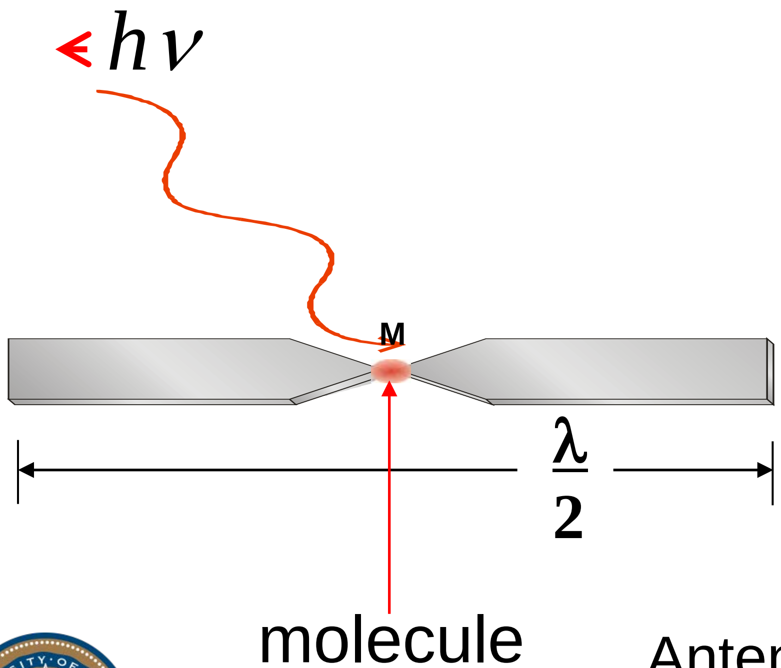
- Room temperature detection of external protons
- No magnetic field gradients needed
- 13 nm^3 detection volume PMMA ~8nT sensitivity
- Collaboration with IBM Research Division

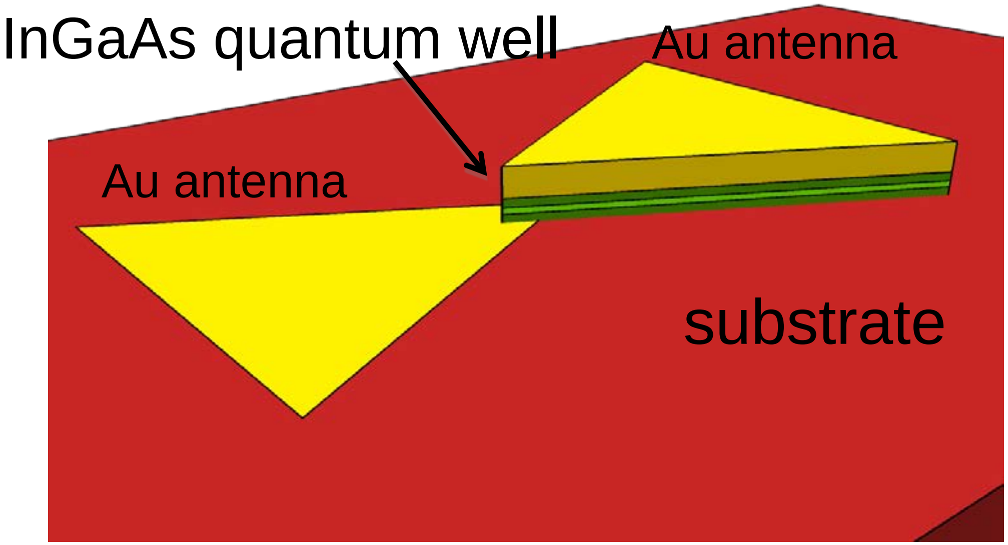
Science, in press (2012)

Spontaneous Hyper-Emission

Eli Yablonovitch & Ming Wu, UC Berkeley

Using an optical antenna, Spontaneous Emission Rate can be ~$0.1\times\omega_o$!!!
Faster than stimulated emission, but antenna slot must be very narrow.

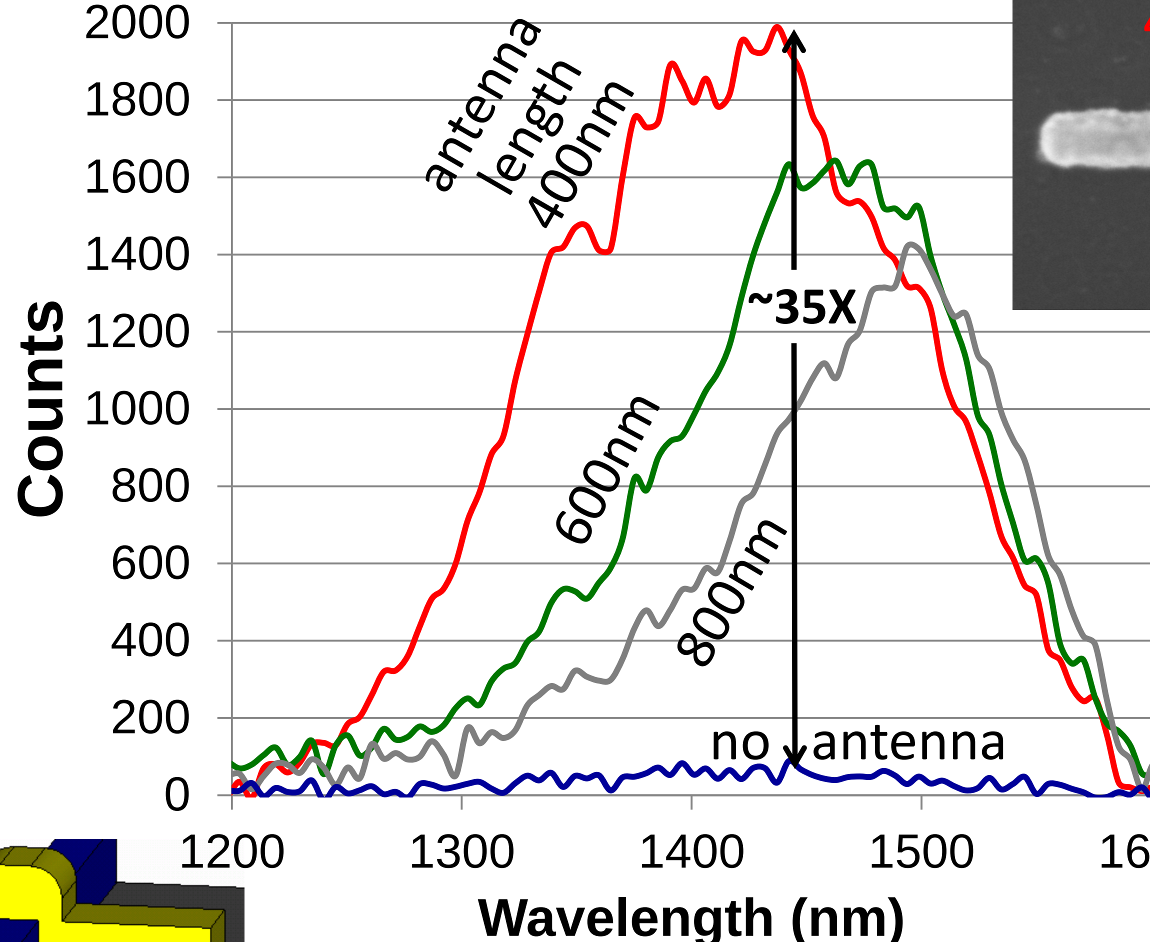


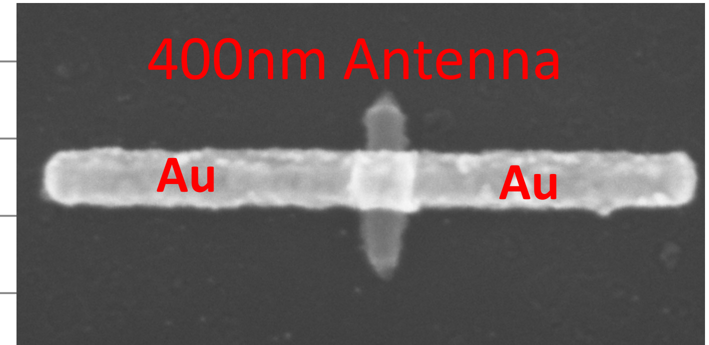


Antenna slot defined by quantum well thickness!

Single Arm Antenna

Eli Yablonovitch & Ming Wu, UC Berkeley

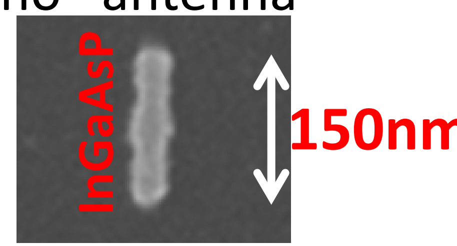


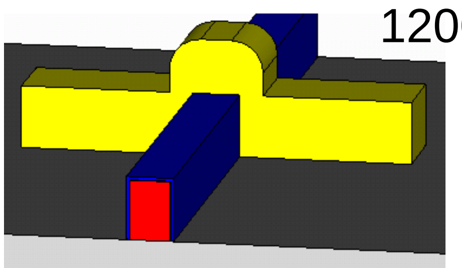


Emission Parallel to Antenna

Pump Polarization

no antenna

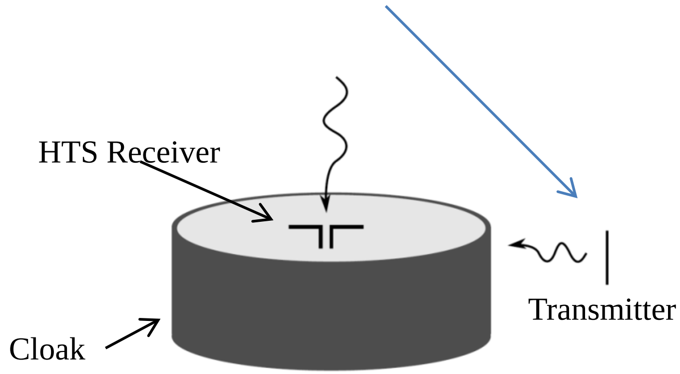




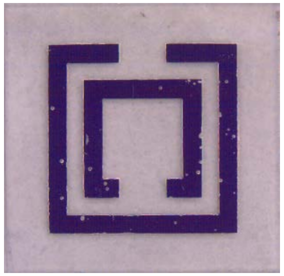
~35X Spontaneous Emission Enhancement

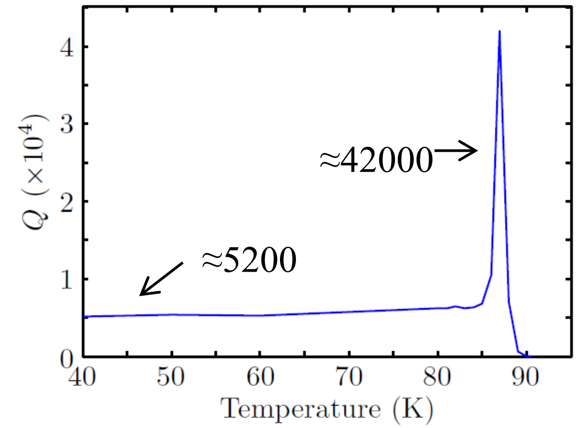
Protecting Superconducting Antennas with Metamaterial Cloaks

Frank Trang, Horst Rogalla, Zoya Popovic, University of Colorado, Boulder

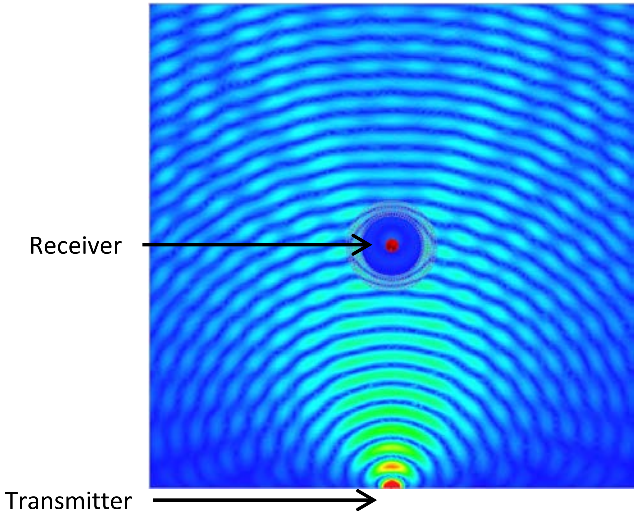


Proposed cloak geometry

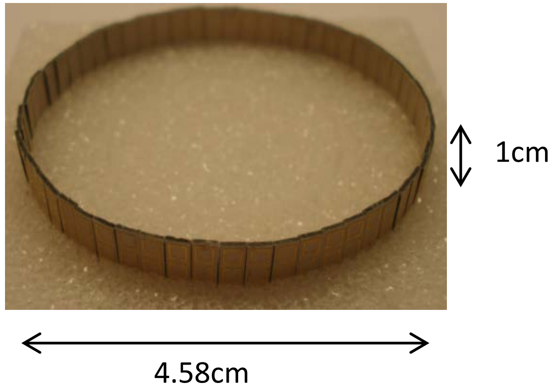




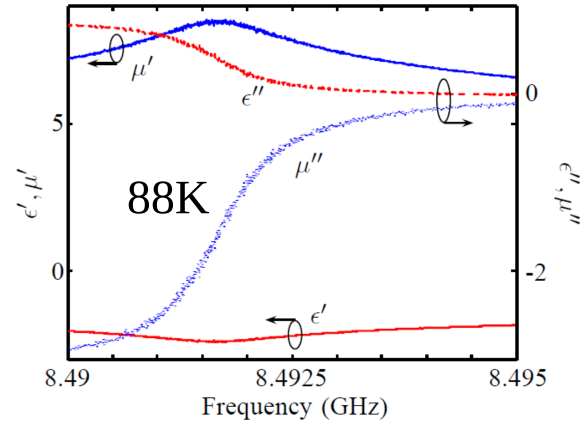
HTS Split Ring Resonator (SRR) and its temperature dependent quality factor Q



Simulated EM-field: the far field is restored behind the cloak



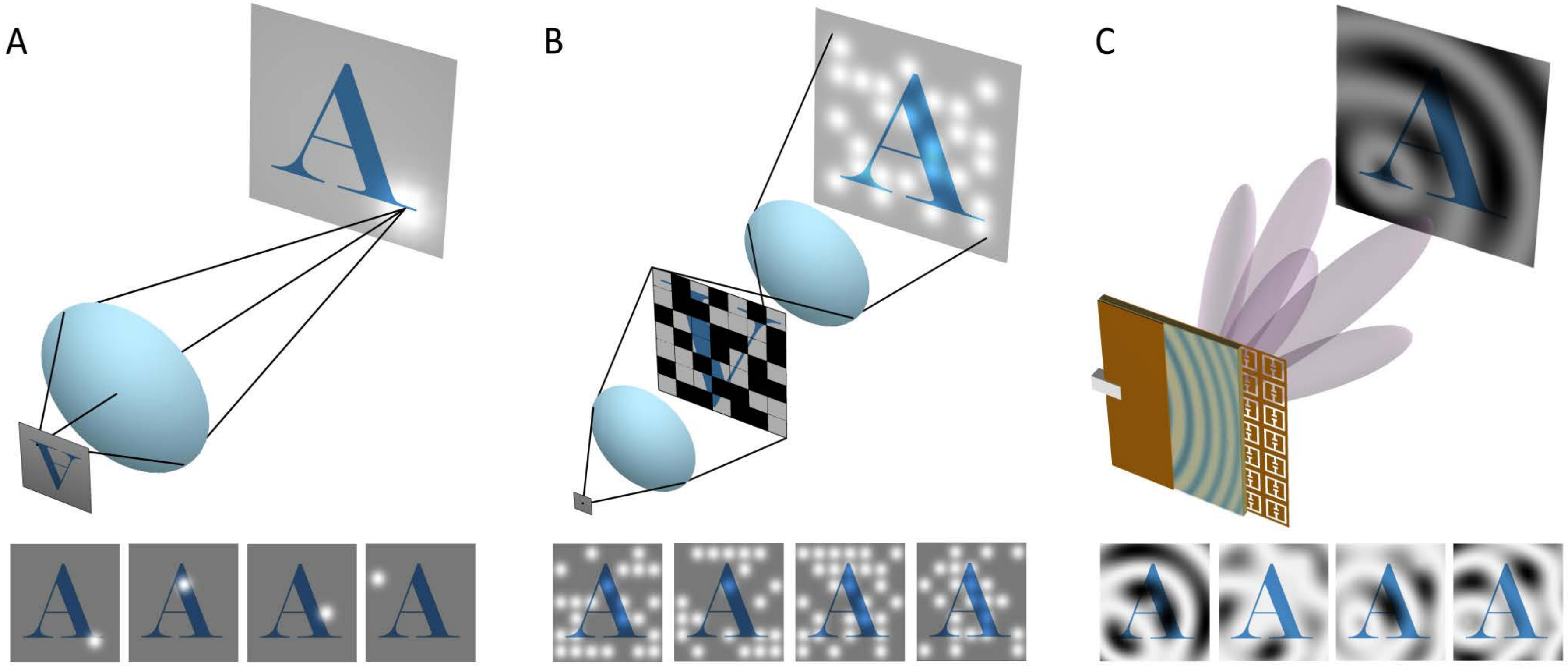
One of 5 layers of the proposed cloak constructed of SRRs.



Parameter extraction of μ and ε

Metamaterials for Computational Imaging

D. R. Smith, *Duke University*

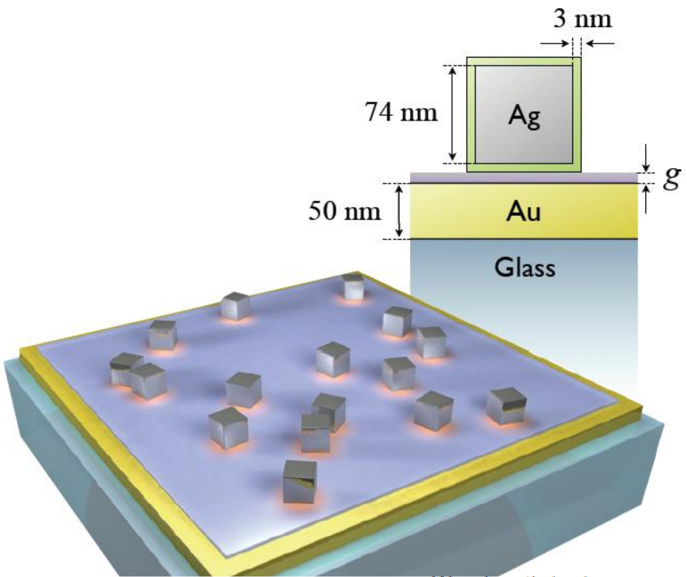


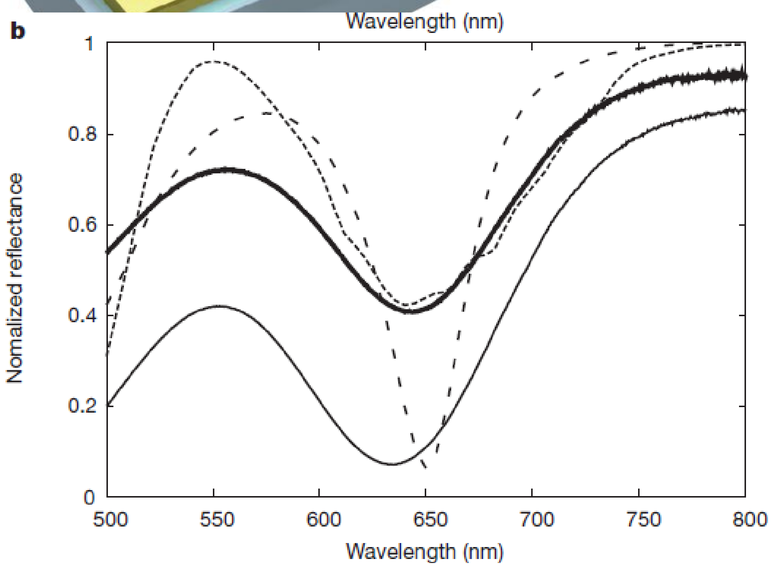
Comparison of (A) conventional, (B) single pixel, and (C) metamaterial imagers. In the metamaterial imager, a set of randomized modes sequentially samples a scene. Scene data can subsequently be reconstructed using sparse algorithms. The imager shown makes use of frequency-diversity to sample an image: no active tuning or mechanical scanning is necessary—just a frequency sweep.

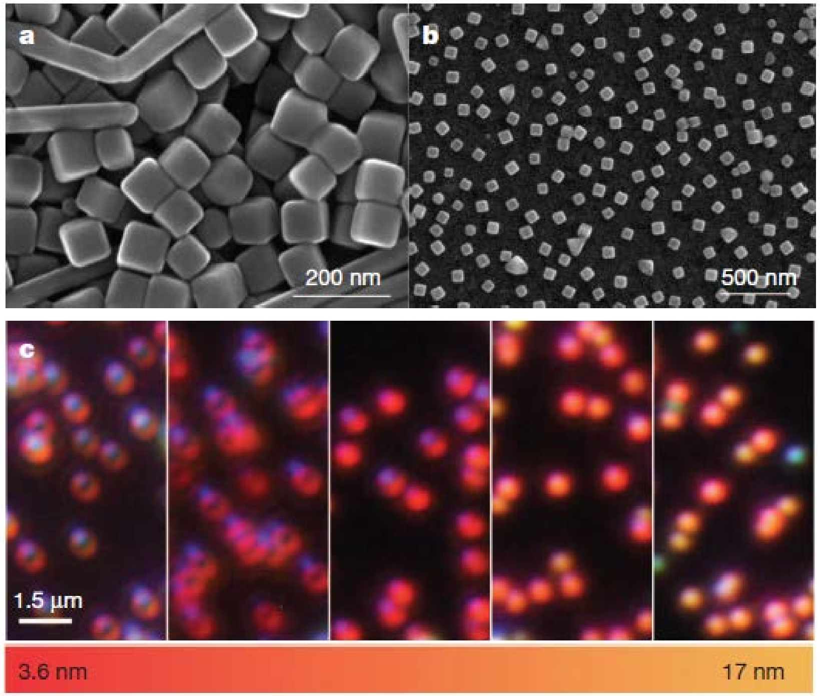
J. Hunt *et al.*, *Science*, in press

Approaches to Large Area Absorber Materials

David R. Smith, Duke University







Film-coupled nanocubes can produce strong absorption resonances that can create surfaces with controlled reflectance. The advantage is that perfect absorbing materials with large surface area can be fabricated cheaply and easily.

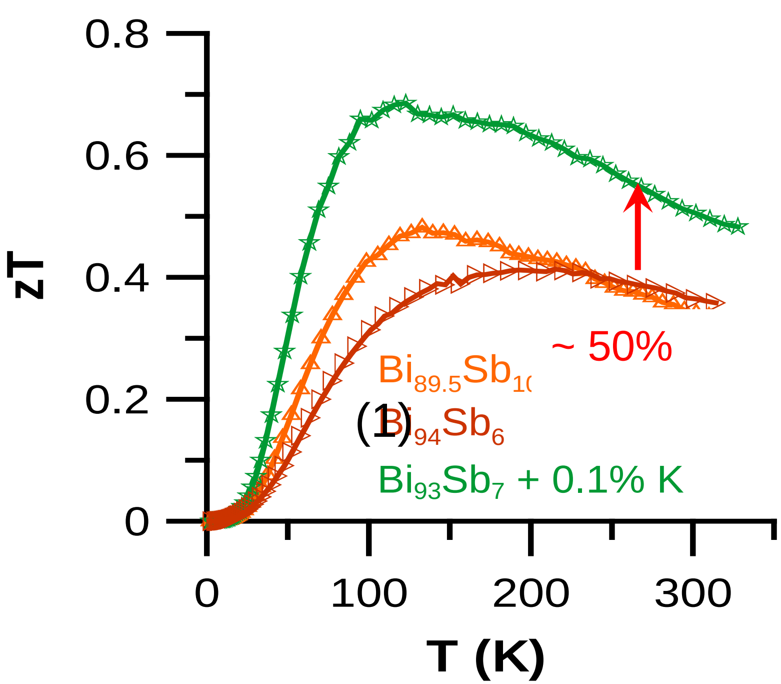
A. Moreau *et al.*, *Nature* (2012)

Cryogenic Peltier Cooling: record zT

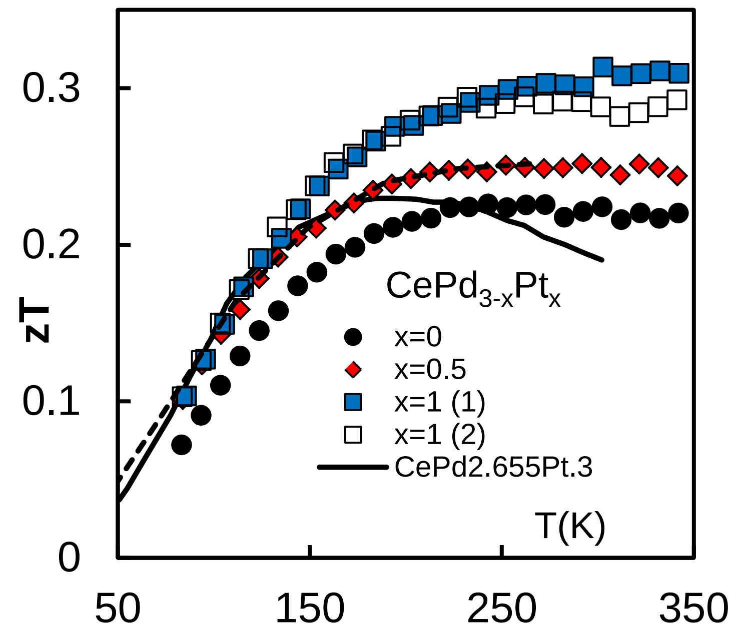
J. P. Heremans *Ohio State; D. T. Morelli, Michigan State*

Record Thermoelectric Figure of Merit $zT \equiv T\,S^2\sigma/\kappa$ below 150 K

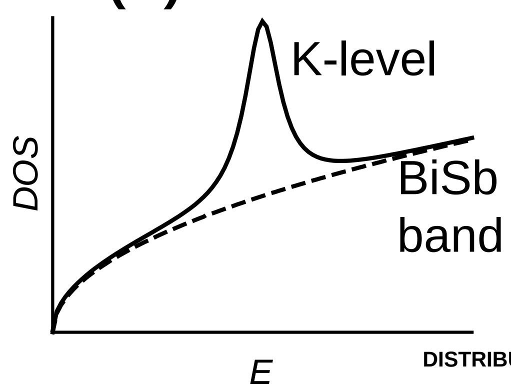
n-type material: $Bi_{93}Sb_7$:K



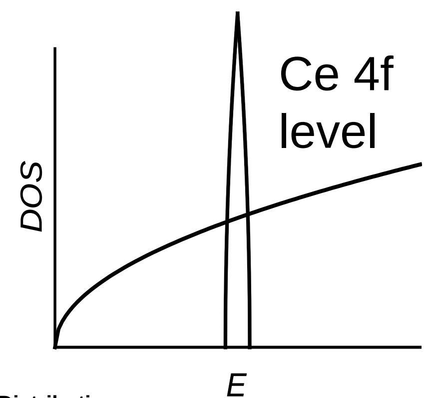
p-type material: $CePd_2Pt$



Principle:
K is a resonant level in BiSb



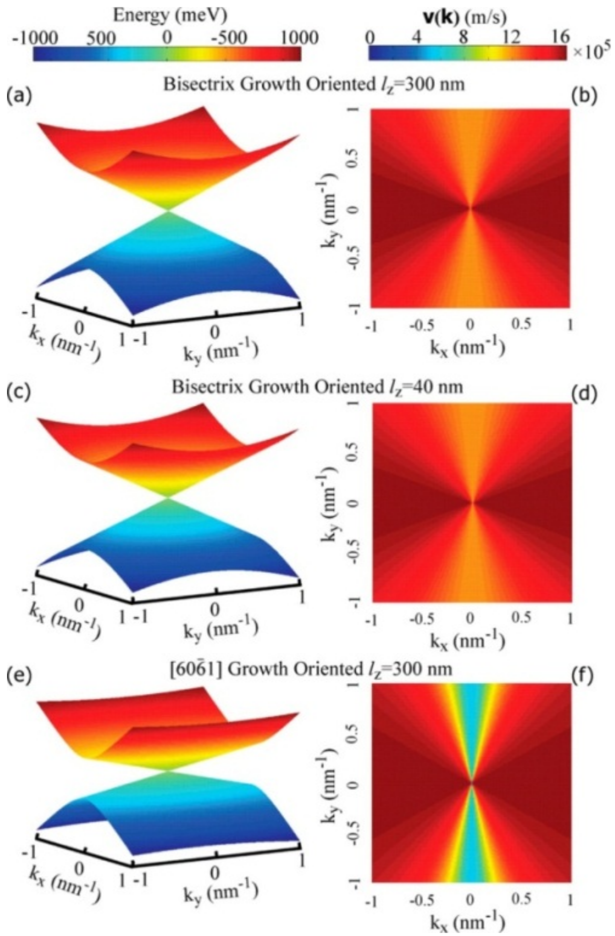
Principle:
Tune E_F in the Ce - 4f level



Dirac cones in BiSb and Electron Cloaking

M. S. Dresselhaus and Gang Chen, MIT

Dirac dispersion relations in BiSb alloy thin films



Modulation doping with impurities in core-shell nanoparticles

Nanoparticles invisible to free electrons